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Stator Converter Controlled Induction Generators (SCIGs)

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5.1 Introduction

As already discussed at length in [Chapter 4](#), the cage rotor induction generator with fixed capacitance self-excitation produces output at slightly variable frequency with load even at regulated (constant) prime-mover speed. Many electrical loads are, however, frequency and voltage sensitive. On the other hand, variable speed generation is needed in many applications to extract more energy from the primary source (wind, water energy).

Power electronics control in the stator of cage rotor induction generators may be used to allow variable speed operation for two situations:

- Grid or stand-alone operation with constant alternating current (AC) voltage and frequency output
- Stand-alone operation with rectifier (direct current [DC]) loads

AC output stator converter controlled induction generator (SCIGs) require AC–AC (cascaded or direct) full power rating static converters. Nowadays, they are fabricated, for variable speed drives, with $\pm 100\%$ reactive and $\pm 100\%$ active power capabilities by proper design, and they are roughly only 50% more expensive than the stand-alone diode rectifier power voltage source insulated gate bipolar transistor (IGBT) inverters produced for up to 2 to 3 MW per unit.

The costs of a full power rating converter — with $\pm 100\%$ active and reactive power capabilities — may be justified by the large motoring and generating speed range and reactive power (or voltage) control and flexibility in power grid applications. For reactive loads, the forced commutated IGBT rectifier and capacitor filter, eventually, with a boost DC–DC converter, is sufficient to control the converter DC voltage output for variable speed.

In applications where the prime-mover power decays sharply with speed (with cubic speed, for example, in wind turbines), it may be sufficient to locate an additional winding in the stator with a larger number of poles $p_1' > p_1$ (say 6/4, 8/6) and use an AC–AC converter for this auxiliary winding, to augment the power of the power winding of the stator that is directly connected to the grid.

The two windings may work simultaneously or successively. The four-quadrant converter operation is very useful to produce additional output above synchronous speed $n_i = f_1/p_1$. Alternatively, for lower speeds, the auxiliary winding may work alone at variable speed to tap the energy below 25% of rated power. We will explore in some detail the above configurations.

5.2 Grid Connected SCIGs: The Control System

SCIGs may be read as stator converter induction generators or cage rotor induction generators. There are two basic schemes:

- With AC–AC cascaded pulse-width modulator (PWM) converter (Figure 5.1a)
- With direct AC–AC PWM converter (Figure 5.1b) [1,2]

The configurations with thyristor DC current link AC–AC converter and, respectively, with thyristor cycloconverter seem to be merely of historical interest, as their reactive power drainage and current harmonics content are no longer acceptable in terms of power quality standards.

While the matrix converter is still in advanced laboratory status, the cascaded AC–AC PWM converter is available off the shelf for powers up to 1 MW and more, with up to $\pm 100\%$ reactive power capability. The so-called high-voltage direct current (HVDC) light technology uses, in fact, IGBTs in multilevel AC–AC cascaded power converters [3], but for higher DC link voltage levels (tens of kilovolts) for DC power transmission.

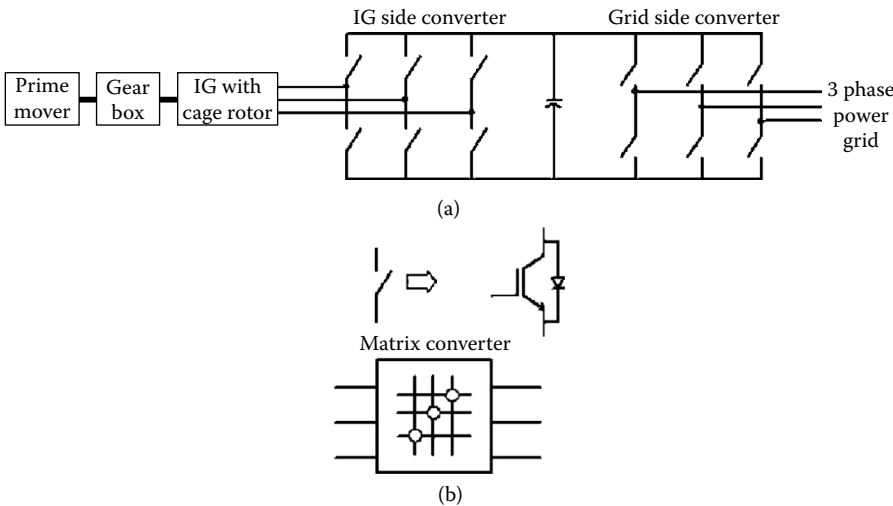


FIGURE 5.1 Grid-connected stator converter controlled induction generators (SCIGs): (a) with cascade alternating current (AC)–AC pulse-width modulator (PWM) converter, and (b) with direct (matrix) converter.

The vector or direct torque control of cascaded PWM converters was applied for variable speed drives with fast and frequent regenerative braking. In essence, the control is similar to that for the case of wound rotor induction generators (WRIGs) with the cascaded converter connected to the rotor ([Chapter 2](#)). What differs is the control and the state estimation for the machine-side converter, as IGs have here a cage rotor.

The motor starting is inherent in the control. Speed, torque, or power control of the machine-side converter may be adopted, depending on the prime-mover operation modes.

For a pump-storage small hydropower unit, motor starting and operation at variable speed are required besides generating at variable speed; for a wind turbine unit, no motoring is, in general, required.

The grid-side converter is controlled for constant DC link voltage and desired reactive power exchange.

5.2.1 The Machine-Side PWM Converter Control

To let the control system open for motoring and generating, let us consider that only torque vs. speed is performed. In essence, a functional generator produces the desired torque vs. speed curve desired from the IG ([Figure 5.2a](#) through [Figure 5.2c](#)). For motor starting, the torque vs. speed may decrease notably with speed ([Figure 5.2a](#)).

In essence, by an *a priori* applied optimization process involving the prime-mover characteristics and IG capability, the optimum torque/speed curves are calculated. From now on, positive or negative torque control is performed with the various torque speed curves stored in tables and called upon according to the operation mode.

For generating, the reference power P^* is set, but then its value is translated into the torque/speed functional reference generator ([Figure 5.3](#)).

The direct torque and flux control (DTFC) seems to be inherent to the application once torque control is required. Stator flux (Ψ_s) control is added, and thus, the control system becomes robust and presents fast response. The stator flux functional may also be expressed in terms of flux vs. torque, to minimize the losses in the IG over the whole speed and power range. The space-vector modulation (SVM) is added to further reduce the IG current harmonics, converter losses, and noise.

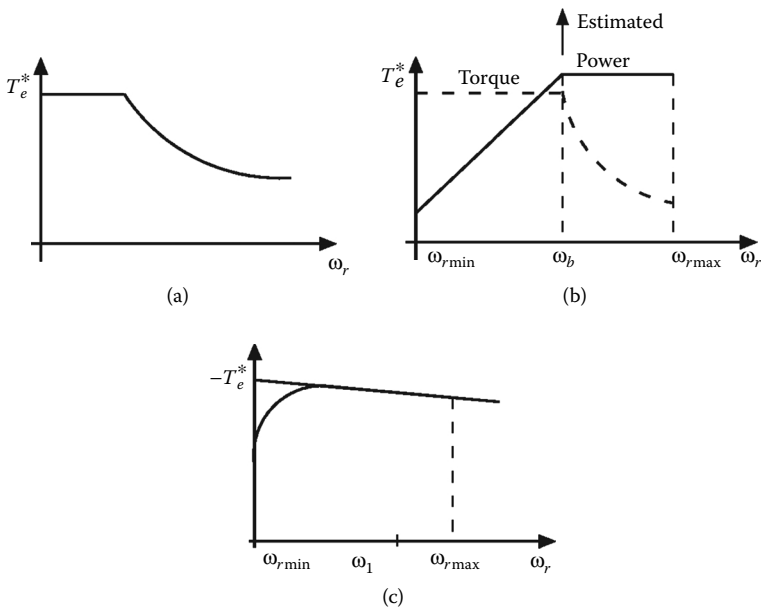


FIGURE 5.2 Typical desired torque/speed curves: (a) for motor starting and operation, (b) for wind turbines stall regulated, and (c) for uncontrolled microhydropoturbine.

- Convergence quickness
- Behavior at zero, very low, and very high rotor speeds
- Complexity and costs of digital implementation vs. performance

For a practical overview on state observers for motion sensorless control, see Reference [8]. From the myriad of proposed state observers for motion sensorless control, we treat here only the sliding mode state observers and direct torque and flux controllers, as they demonstrate the following attributes:

- Capable of good accuracy down to 3 to 5 rpm in speed control and to zero speed in torque control mode
- Robust once the stator resistance is corrected through an estimator
- Capable of working for the entire speed range without making changes in software or hardware

We will treat separately, for convenience, only the flux–torque observer and the speed observer issues. To decouple the flux observer from the speed observer errors, the former is conceived as inherently speed sensorless. The typical form of the sliding mode flux observer is based on the induction machine (IM) space-phasor model [8]:

$$\frac{d\hat{\Psi}_s}{dt} = -R_s \hat{I}_s + \hat{V}_s + K_1 \text{sgn}(\bar{I}_s - \hat{I}_s) + K'_1(\bar{I}_s - \hat{I}_s) \quad (5.1)$$

$$\frac{d\hat{\Psi}_r}{dt} = \frac{L_m}{L_r T_r \sigma} \hat{\Psi}_s - \left(\frac{1}{T_r \sigma} + j(\omega_{\psi_r} - \omega_r) \right) \hat{\Psi}_r + K_2 \text{sgn}(\bar{I}_s - \hat{I}_s) + K'_2(\bar{I}_s - \hat{I}_s) \quad (5.2)$$

where

R_s is stator resistance

L_m is magnetization inductance

L_r is total rotor inductance $T_r = L_r/R_r$

R_r is rotor resistance

ω_r is rotor speed

$\hat{V}_s$ is the stator voltage vector

$\bar{\Psi}_s, \bar{\Psi}_r$ are the stator and rotor flux vectors

The first equation is written in stator frame ($\omega_b = 0$) and the second in rotor flux frame ($\omega_b = \omega_{\psi_r}$). Consequently, in rotor flux orientation, the term in $j(\omega_{\psi_r} - \omega_r)$ disappears. This is how the state observer is becoming inherently speed sensorless. Also, the stator and the rotor flux observers use combined sliding mode nonlinear and linear feedback terms $S_s = \bar{I}_s - \hat{I}_s$: coefficients K_1, K_2 , and K'_1, K'_2 .

To further reduce chattering, the “sgn” functional may be replaced by

$$\text{sat}(x) = \begin{cases} \text{sgn}(x) & \text{if } |x| > h \\ \frac{x}{h} & \text{if } |x| \leq h \end{cases} \quad (5.3)$$

A low-pass filter on the local dynamics of the functional S_s is obtained. To compensate for the inevitable offset in voltage or current measurements, the terms are replaced by

$$K_{1,2}^\sigma = \left| \begin{array}{c} K_1 + \frac{K_{11}}{s} \\ K_2 \end{array} \right| \quad (5.4)$$

A typical embodiment of such a sliding mode plus linear flux observer is depicted in Figure 5.4 [8].

The reduction in error with offset compensation of a 0.3 V voltage offset is shown in Figure 5.5a and Figure 5.5b.

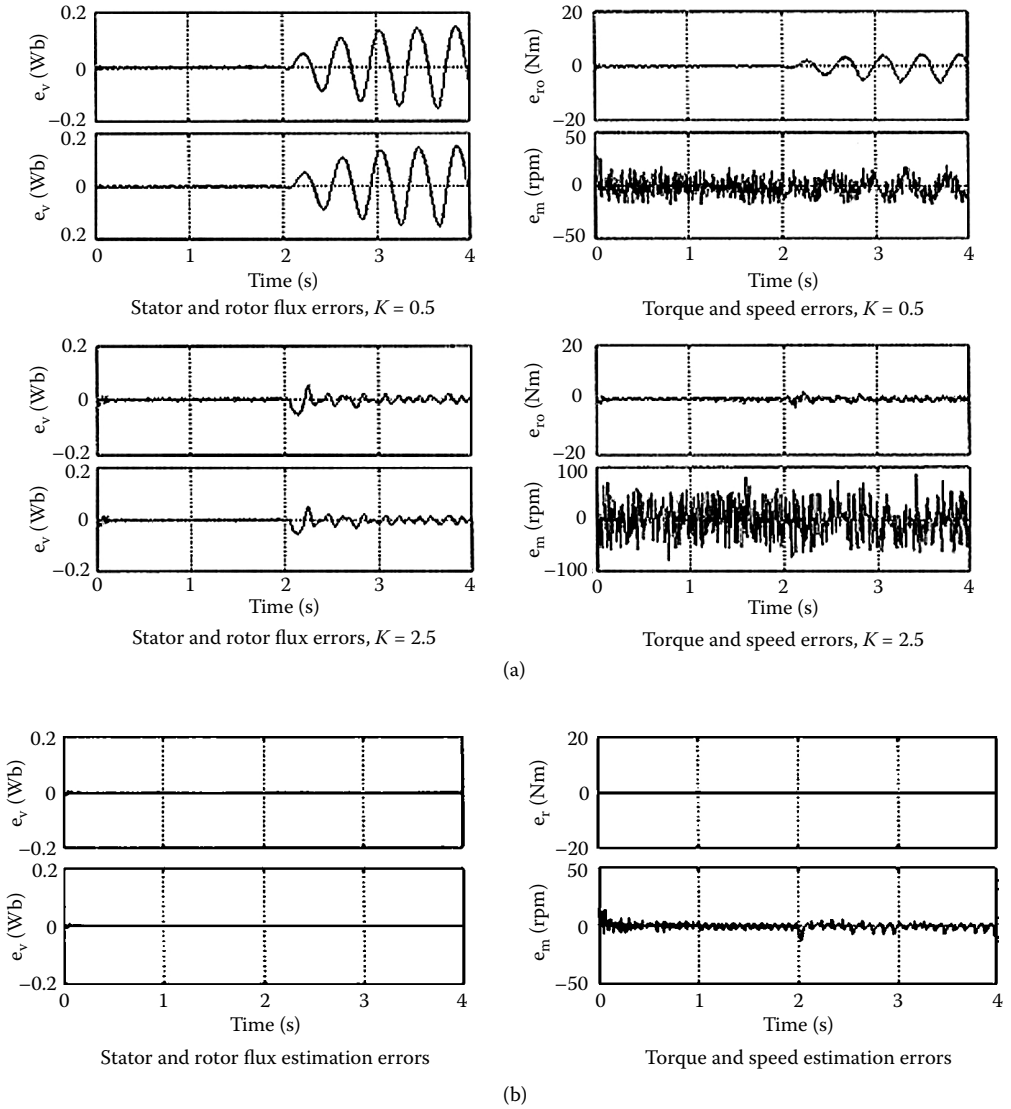


FIGURE 5.5 Voltage offset compensation 0.3 V in flux, torque, and speed errors: (a) two gains $K = 0.5, 2.5$ and (b) modified SM (5.4) $-K_p = 20, K_i = 80$.

$$\hat{\omega}_{\psi_r} = \frac{\hat{\Psi}_{r\beta}(k) \cdot \hat{\Psi}_{r\alpha}(k-1) - \hat{\Psi}_{r\alpha}(k) \cdot \hat{\Psi}_{r\beta}(k-1)}{T_{sa} \left(\hat{\Psi}_{r\alpha}^2(k) + \hat{\Psi}_{r\beta}^2(k) \right)} \quad (5.11)$$

$$\hat{\omega}_{slip} = \hat{T}_e \frac{2\hat{R}_r}{3p_1 \hat{\Psi}_r^2} \quad (5.12)$$

with

$$T_e = \frac{3}{2} p_1 \frac{L_m}{L_r} (\hat{\Psi}_{r\alpha}(k) \hat{i}_{s\beta} - \hat{\Psi}_{r\beta}(k) \hat{i}_{s\alpha}) \quad (5.13)$$

The rotor flux vector instantaneous speed $\hat{\omega}_{\psi_r}$ calculator (Equation 5.11) includes the sampling time T_{sa} .

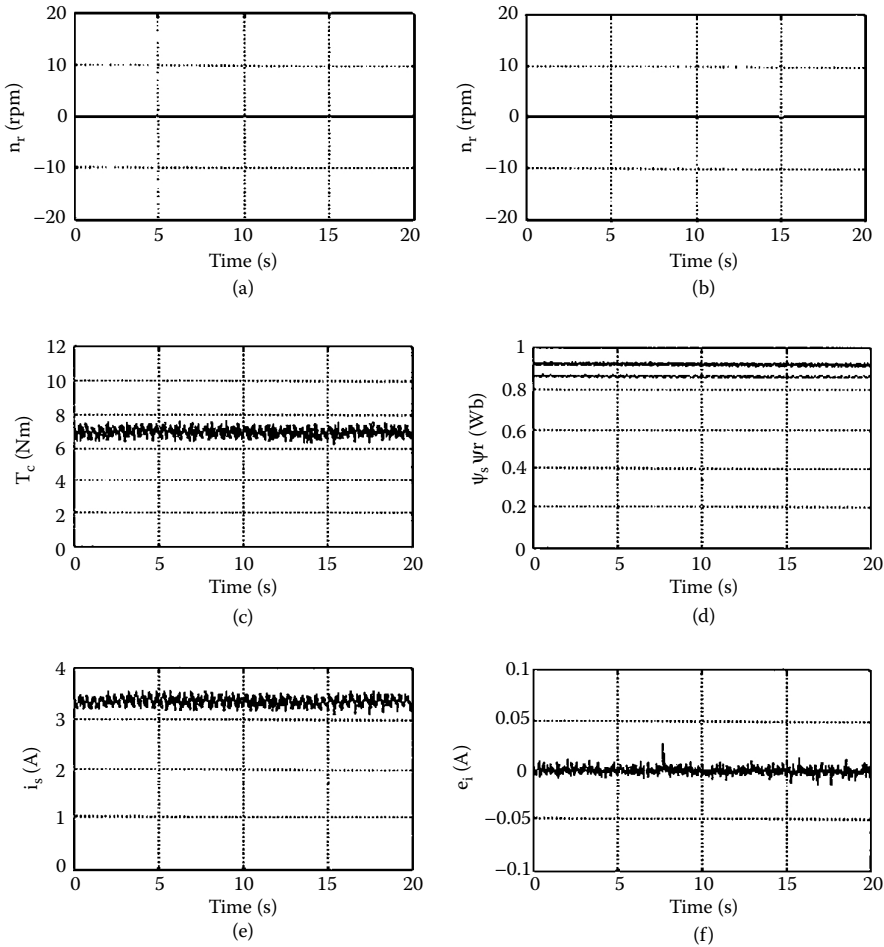


FIGURE 5.6 Zero-speed torque-mode sensorless with sliding mode flux observers: (a) estimated rotor speed, (b) measured rotor speed, (c) estimated torque, (d) estimated stator and rotor flux, (e) estimated stator current magnitude, and (f) stator current estimation error (Adapted from C. Lascu, Direct Torque Control of Sensorless Induction Machine Drives, Ph.D. thesis, University of Politehnica, Timisoara, Romania, 2002.)

5.2.1.2 The DTFC–SVM Block

As explained in [Chapter 2](#) for the WRIG, DTFC was developed as a fast response deadbeat torque and flux control to stand for an alternative implementation to vector control.

The principle of analogy with the DC motor, embedded on vector control, is replaced in DTFC by stator flux direct acceleration or deceleration and increasing or decreasing amplitude. An adequate combination of voltage vectors in the PWM voltage source converter is triggered based on torque error, flux error signs, and stator flux vector position in one of the six, 60° wide, sectors of an electrical period ([Figure 5.8](#), [9]).

For torque control only, the speed estimation is not even required. For speed control it is. Also, the speed estimator is needed when the prime mover speed control is operated in an SCIG application.

The original DTFC is characterized by the following:

- Fast dynamic response in torque and flux
- Robustness
- No need for current controllers
- Simplicity

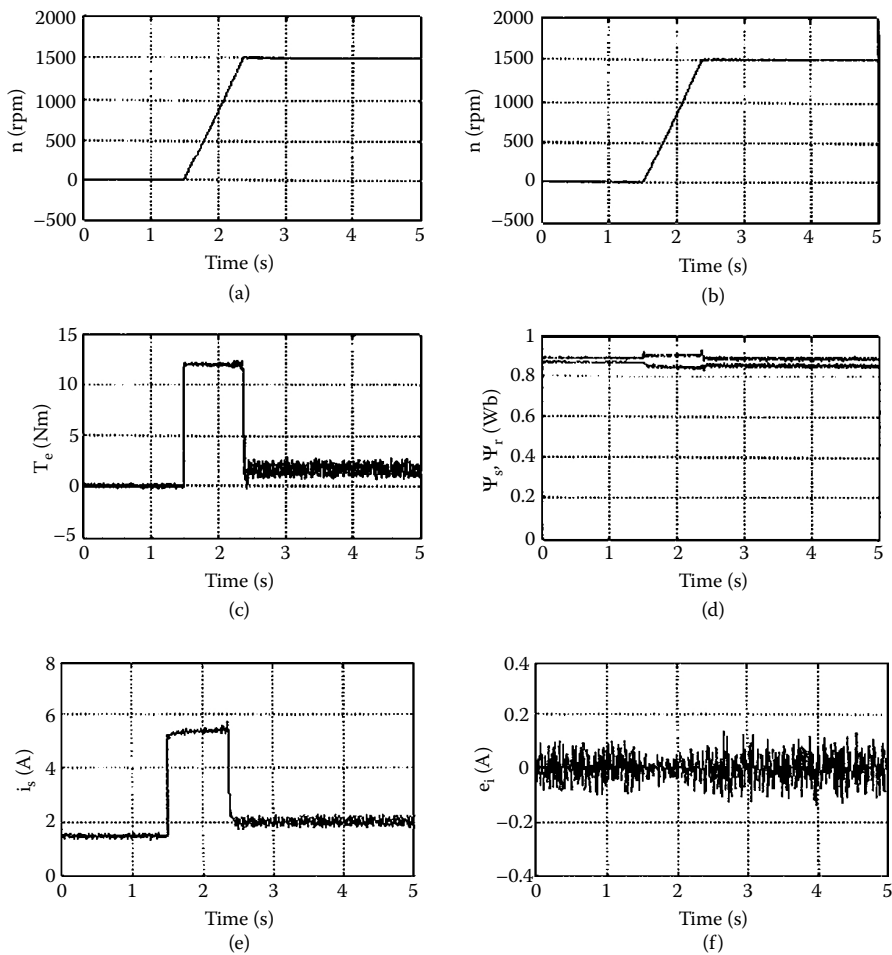


FIGURE 5.7 Acceleration transients with sensorless direct torque and flux control (DTFC) for a 1.1 kW induction machine (IM): (a) estimated rotor speed, (b) measured rotor speed, (c) estimated torque, (d) estimated stator and rotor flux, (e) estimated stator current magnitude, and (f) stator current estimation error.

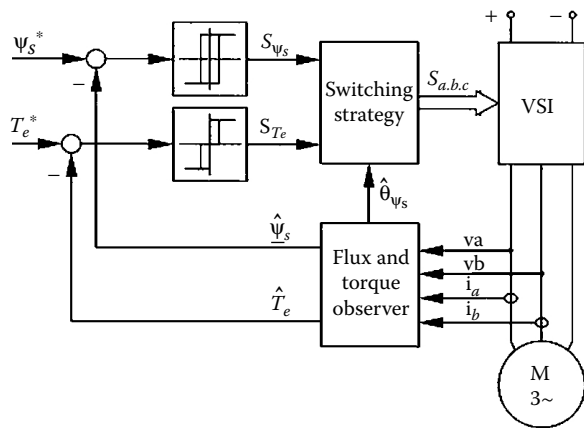


FIGURE 5.8 Original direct torque and flux control (DTFC) of an induction machine (IM).

- Inherent sensorlessness (no rotor position is required for control)
- High torque and current ripple
- Voltage source inverter (VSI) switching frequency that is variable
- High acoustical noise at low speeds
- Steady-state torque error

To take advantage of DTFC qualities but circumvent its difficulties, the space-vector modulation (SVM) [9] together with various implementations of torque and flux regulators were successfully introduced [10]. Variable structure torque and flux controllers (VSCs) plus SVM solutions are presented here [9–11].

Basically, the d – q voltage components $V_d^* V_q^*$ are calculated from flux and torque errors ε_{ψ_s} ε_{T_e} by combining proportional integral (PI) with sliding mode control. The sliding mode functional vector is S_s :

$$S_s = S_{\psi_s} + jS_{T_e} = \varepsilon_{\psi_s} + j\varepsilon_{T_e} \quad (5.14)$$

$$V_{sd}^* = \left(K_{P\psi} + \frac{1}{s} K_{I\psi} \right) (\varepsilon_{\psi_s} + K_{Vsc\psi} \text{sgn}(S_{\psi_s})) \quad (5.15)$$

$$V_{sq}^* = \left(K_{PTe} + \frac{1}{s} K_{ITe} \right) (\varepsilon_{T_e} + K_{VscTe} \text{sgn}(S_{T_e})) + \hat{\omega}_{\psi_s} \hat{\Psi}_s \quad (5.16)$$

Equation 5.15 and Equation 5.16 reveal the combination of PI and nonlinear (sliding mode) regulators and also the motion electromagnetic field (emf) compensation ($\hat{\omega}_{\psi_s} \hat{\Psi}_s$). Again, the stator flux speed $\hat{\omega}_{\psi_s}$ (estimated earlier in this paragraph), and not the rotor speed, is required. The block diagram of the stator flux and torque linear and discontinuous (SM) controllers is shown in Figure 5.9.

The reference stator voltages $V_{ds}^* V_{qs}^*$ in stator flux coordinates are transformed by the Park transformation:

$$\begin{bmatrix} V_a^* \\ V_b^* \\ V_c^* \end{bmatrix} = \begin{bmatrix} \cos(\theta_{\psi_s}) & -\sin(\theta_{\psi_s}) \\ \cos\left(\theta_{\psi_s} - \frac{2\pi}{3}\right) & -\sin\left(\theta_{\psi_s} - \frac{2\pi}{3}\right) \\ \cos\left(\theta_{\psi_s} + \frac{2\pi}{3}\right) & -\sin\left(\theta_{\psi_s} + \frac{2\pi}{3}\right) \end{bmatrix} \cdot \begin{bmatrix} V_{ds}^* \\ V_{qs}^* \end{bmatrix} \quad (5.17)$$

From now on, an open loop PWM technique may be used to “construct” the stator voltage waveforms [9, 11]. The operation of such an IM sensorless 1.1 kW drive with DTFC–SVM during ± 6 rpm speed reversal under full load is indicative of good performance (Figure 5.10a through Figure 5.10h).

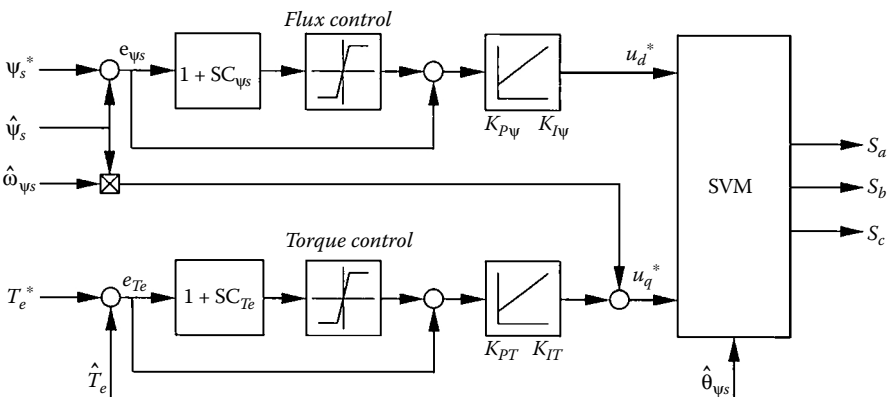


FIGURE 5.9 Linear and SM feedback direct torque and flux control (DTFC).

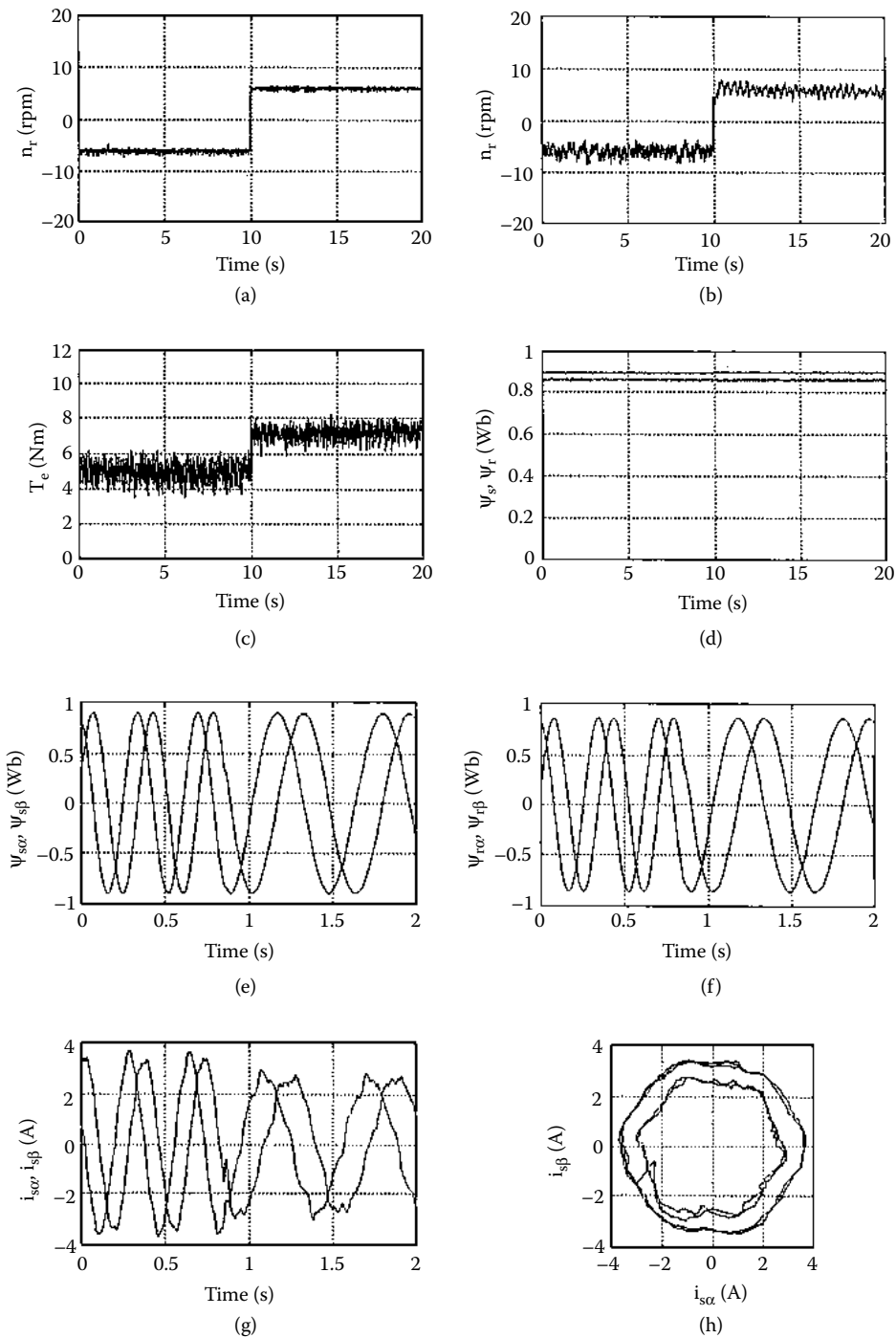


FIGURE 5.10 Sensorless operation for ± 6 rpm speed reversal under full load with linear plus SM direct torque and flux control (DTFC)–space vector modulation (SVM) control: (a) estimated rotor speed, (b) measured rotor speed, (c) estimated torque, (d) estimated stator and rotor flux, (e) estimated (α, β) stator flux, (f) estimated (α, β) rotor flux, (g) estimated (α, β) stator current, and (h) estimated stator current trajectory.

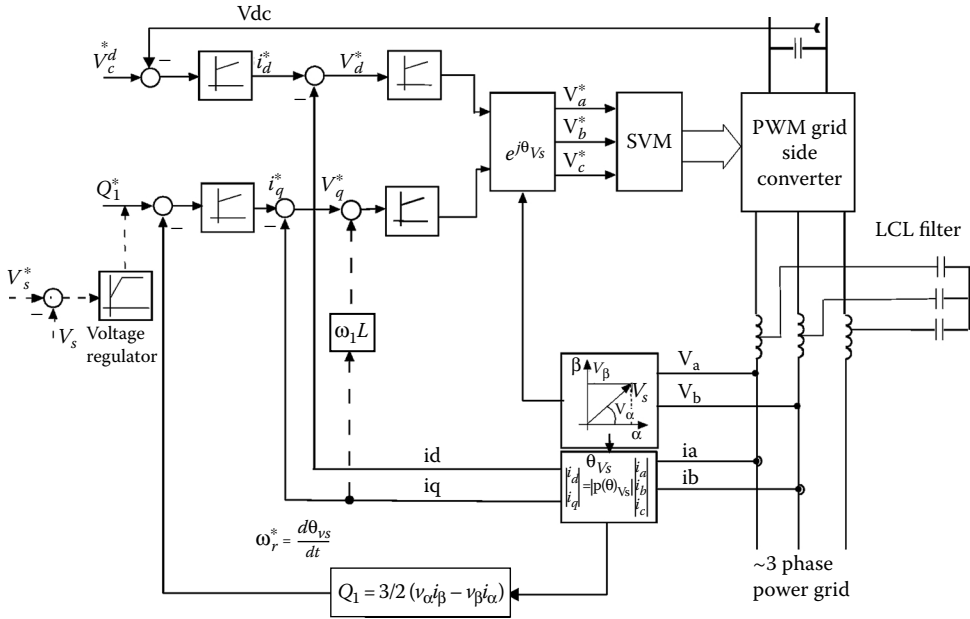


FIGURE 5.11 The grid-side pulse-width modulator (PWM) converter control.

While DTFC–SVM sensorless control with linear and SM controllers and observers was illustrated for an IM drive, the same may be used directly in the SCIG control system shown in Figure 5.3.

5.2.2 Grid-Side Converter Control

Grid-side converter control is, in general, standard vector control, where DC link voltage control provides for active power from (to) DC link voltage to (from the power grid, while reactive power control provides for reactive power exchange with the power grid), (Figure 5.11). The reactive power exchange with the power grid is, in fact, provided by the oversized DC link capacitor, which also “covers” the IG magnetization.

The active power exchange is controlled through the machine-side converter from (to) the IG. Adequate voltage and capacitance oversizing of the DC link may provide for up to $\pm 100\%$ reactive power exchange Q_1^* , which is so useful in the local power grid voltage control and stabilization. Q_1^* may be commanded by the grid voltage error with respect to a desired value. The DC link reference voltage V_{DC}^* is generally kept constant under normal operation circumstances, but it may be reduced in relation to reactive power requirements.

When an inductance-capacitance inductance (LCL) filter is introduced between the grid-side converter and the grid, speed decoupling of filter inductance L along the q axis current control is added, to construct V_q^* (Figure 5.11). The measured frequency of power grid voltage ω_1 is required for decoupling, to speed up the response in the presence of the power filter.

5.3 Grid Connection and Four-Quadrant Operation of SCIGs

Consider the case of a microhydroturbine, also capable of pumping operation, that needs variable speed during generating periods to eliminate the speed governor and provide for good overall turbine efficiency for variable water heads.

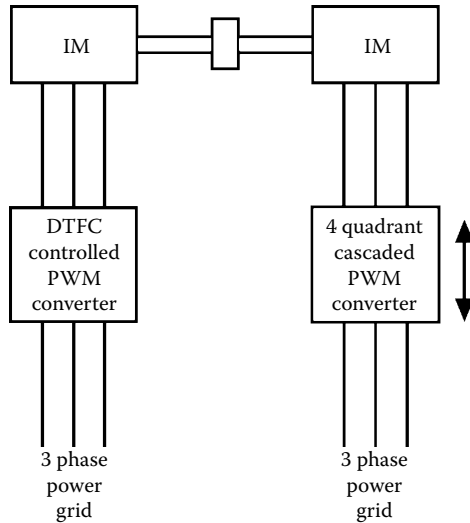


FIGURE 5.12 Testing stator converter controlled induction generator (SCIG) to the power grid.

The standard synchronous generator solutions require speed governing in the microhydroturbine for constant speed, to provide constant frequency. Also, the acceleration and the synchronization take time, as they are done by the turbine and are not protected from severe transients.

The SCIG, on the other hand, may start with the IG in motoring by fixing a positive torque reference to the machine-side converter to complement the unregulated torque contribution of the turbine, after the water gate is opened. The acceleration is fast, and the “synchronization” sequence is eliminated. All that is needed is to set a negative reference torque (or power P_1^*) to control the system and a positive (or negative) reactive reference Q_1^* to the grid-side converter. If pumping is required, the positive torque (power) reference is maintained and tailored to speed to best exploit the pump induction motor system up to 20 to 50% above base (rated) speed $n_1 = \frac{f_{1b}}{P_1}$. For better pumping, the turbine pump needs more speed than that needed for good turbinning.

Experiments were performed on a laboratory system using two 10 kW cage rotor IMs, one playing the role of the turbine and the other the role of the SCIG (Figure 5.12). The 25 kVA four-quadrant cascaded PWM AC–AC converter was an off-the-shelf device intended for variable speed drives with fast regenerative braking of large inertia loads.

The turbine was emulated by a variable speed drive in speed control mode. Starting can be performed either by the “turbine” up to a preset speed or simultaneously by the turbine and the SCIG in the motoring mode.

Steady-state operations at the power grid in generating for 0 and 50% reactive power delivery are illustrated in (Figure 5.13a and Figure 5.13b).

The power grid current evolution when, for –100% reference torque (generator) at the IG side converter, control input is maintained, and the speed is ramped down by “turbine” control from 1500 to 800 rpm is shown in Figure 5.14.

Rather smooth generating to motoring transients were obtained. Grid current vs. voltage waveforms during motoring acceleration (for pumping) at zero reactive power exchange with the power grid are shown in Figure 5.15. Full four-quadrant operation was thus performed.

It goes without saying that “synchronization” has become an irrelevant concept, as it can be done at variable speed. Also the disconnection from the power grid can be done smoothly via the grid-side and machine-side converters. The two converters provide flexibility and opportunities for various actions, should power grid faults occur.

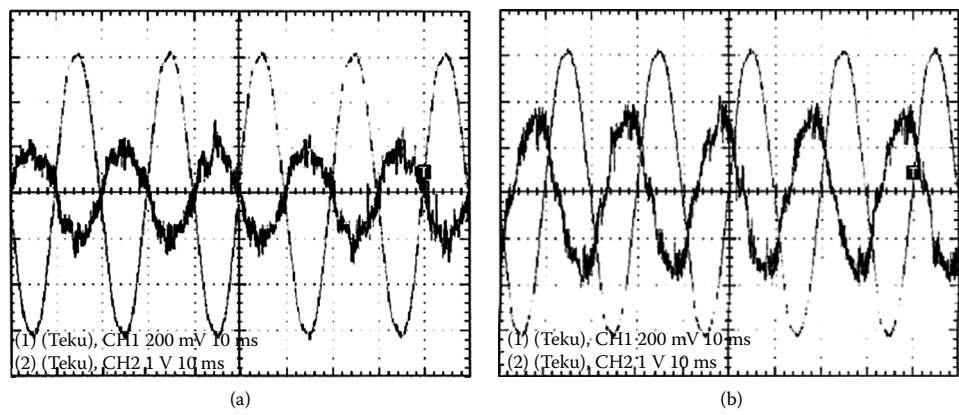


FIGURE 5.13 Steady-state generating at the power grid (1500 rpm), voltage and current at (a) zero reactive power and at (b) 50% reactive power delivery and 100% torque.

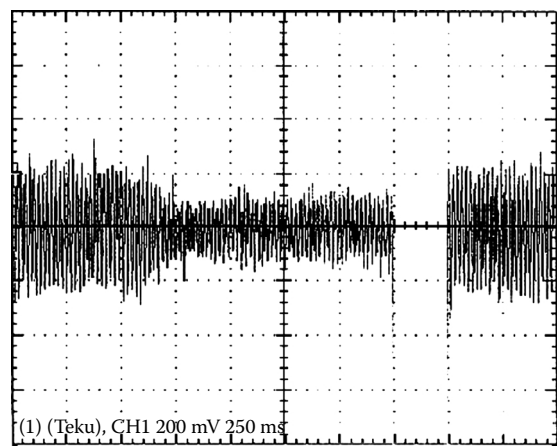


FIGURE 5.14 Grid phase current for generating at 100% torque when speed is ramped down by the turbine control from 1500 rpm to 800 rpm.

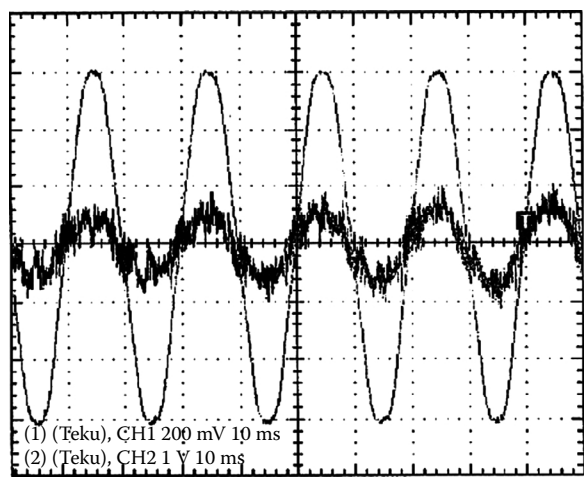


FIGURE 5.15 Grid voltage and current during acceleration for motoring.

The full rating of a four-quadrant AC–AC cascaded PWM converter turns out to be a performance asset, as it controls the whole power exchanged with the grid: active and reactive. All of this comes at higher costs than in WRIGs, where the rating of the four-quadrant cascaded AC–AC PWM converter is 25 to 30% of the rated power. The latter, however, has tight control only on $\pm 25\%$ of the power. It should be noted that the commercial four-quadrant PWM IGBT converter used in our experiments and built for drives requires additional LCL filtering between the grid-side converter section and the power grid to improve the current waveforms in order to fully comply with the contemporary strict power quality standards.

Load rejection of SCIG at the power grid with controlled turbine tends to lead to overspeeding, unless a ballast (alternative) load is provided in the DC voltage link. But, this represents a transition from power grid to stand-alone operation, which will be discussed next.

5.4 Stand-Alone Operation of SCIG

In stand-alone operation, the SCIG is considered the only source meant to produce constant voltage and frequency output.

The IG-side converter control may remain the same as that for the grid connection (DTFC, in our earlier presentation). The power (torque) vs. speed reference function generator is again based on optimal utilization of the turbine generator and the available primary energy (water or wind energy). The control of the output voltage and frequency and the power balance between the generator and the load powers are performed through the grid-side PWM converter, which needs alteration in comparison to the grid connected operation mode. Current limitation means, through the control, are required along with voltage feed-forward and filter inductance L decoupling.

A DC voltage limiter V_{DCmax} triggers a DC–DC converter that feeds a resistive load connected in the DC link, to balance the generator to load power. Finally, a battery in the DC link is needed to provide initial DC link voltage to initiate the self-excitation of the IG.

All things considered, a generic control system for stand-alone operation would look like that shown in Figure 5.16. The controlled system in Figure 5.16 is basically an indirect voltage vector with current limiters [12]. Vector current indirect control is also possible. The vector control is performed in load voltage orientation and, at least at the initialization, this voltage is zero, so the angle θ_v of the load voltage vector has to first be imposed as follows:

$$\theta_v = \int \omega_1^* dt \quad (5.18)$$

where ω_1^* is the reference load frequency. Moreover, the reference DC voltages V_{df}^* and V_{dc}^* have to be carefully correlated, depending on requested active and reactive power loads and on the LCL filter characteristics (to some extent).

As the active power is transmitted through the IG, its control should be placed there, while the reactive power control requirement should govern the V_{qf}^* value. When the load is too large, the V_{dc} controller decreases the reference voltage V_{df}^* by fast action.

Instead of the actual load voltage vector angle in the Park transformation for open loop PWM of V_{df}^* and V_{qf}^* it seems reasonable to use the value from Equation 5.18, as frequency ω_1^* has to be imposed. Full load, applied on 50% load, transient operation of such an 11 kW laboratory system is illustrated in Figure 5.17a and Figure 5.17b [12], for constant speed, in terms of DC voltage V_{dc} and V_d (in fact, load voltage amplitude) responses.

The DC voltage recovers quickly at the reference value after a notable drop. And, V_d (load voltage) recovers quickly, but after a peak, possibly due to the LCL filter intervention.

Note that the grid connected and stand-alone control systems may be integrated and allow for both operation modes and smooth transitions from one to the other [12].

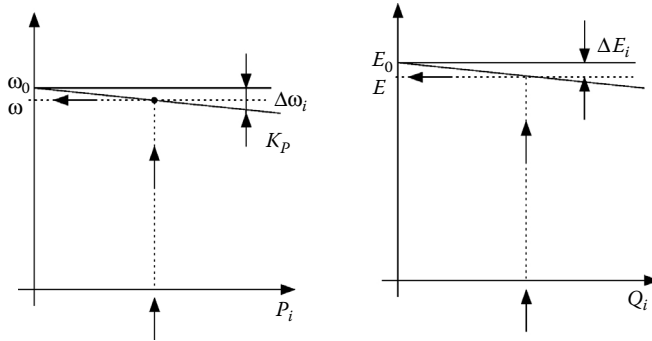


FIGURE 5.18 Frequency and voltage droop curves.

5.5 Parallel Operation of SCIGs

Stand-alone SCIGs are to be connected in parallel, and they have to share equitably the load power (active and reactive). Sharing power “equitably” between PWM converters may be accomplished as done for synchronous generators: through voltage and frequency droop curves (Figure 5.18).

It is well understood that the frequency and voltage in the load are the same for all SCIGs. The active and the reactive power sharing of each SCIG depends on the frequency and on the voltage droops $\Delta\omega_i$, ΔE_i of each component of the group.

If the SCIGs are of different ratings, they have to load in the same proportion to the rated load, in order to ensure maximum output, without overloading too much any of the SCIG components of the group. The load active and reactive power requirements P_i , Q_i have to be measured (estimated) from measured voltages V_a , V_b and currents i_a , i_b . They then should be divided with corresponding weightings among the SCIGs of the group:

$$P_L = \sum C_{P_i}(P_L)P_{i\text{rated}} = \sum P_i \quad (5.19)$$

$$Q_L = \sum C_{Q_i}(Q_L)Q_{i\text{rated}} = \sum Q_i \quad (5.20)$$

The weight coefficients C_{P_i} and C_{Q_i} depend on P_L and Q_L and on the availability, costs, and risks of various SCIGs, as some may be driven by wind turbines, and some by gas turbines, microhydroturbines, or diesel engines.

The frequency and voltage droops of each SCIG decrease with active and reactive power. So, V_{dc}^* and ω_1 should be lowered slightly with power P_i , Q_i to allow for load sharing but not compromise power quality. The transient operation of two single-phase converters in parallel for step power commands is shown in Figure 5.19 [13].

The responses in frequency (Figure 5.19a) reveal clearly the fact that the first converter experiences a reduction in active power (P_1), while the second shows an increase in active power (P_1) (Figure 5.19b). Though the changes in frequencies of the two converters are rather small, they (Figure 5.19a) are decisive for active power sharing. The same rationale applies for changes in voltages.

Going back to the control of each SCIG, it means that we only need to change the V_d^* and ω_1^* (in θ_v^*), accordingly, to active and reactive power requests from that particular SCIG.

Note that handling unbalanced power grid voltages and unbalanced loads in stand-alone operation may be done through separate control of positive and negative sequences. This way, the voltage dips in the power grid are markedly reduced [14].

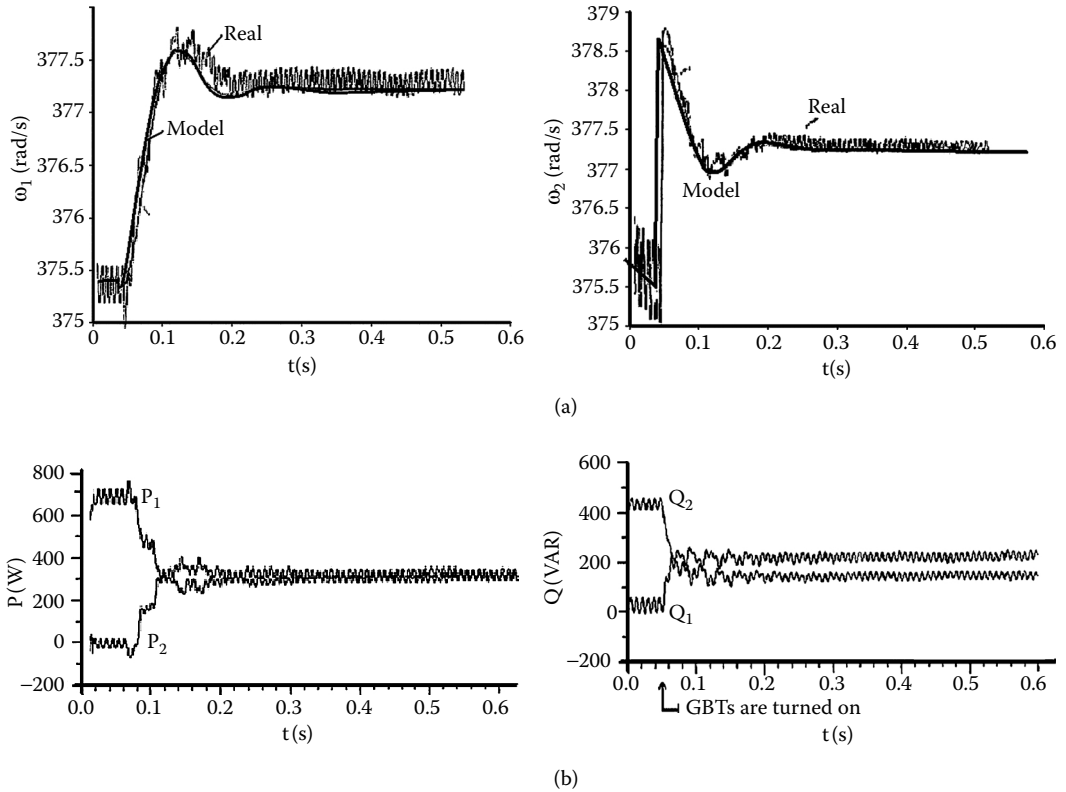


FIGURE 5.19 Two pulse-width modulator (PWM) converters in parallel: (a) frequency and transients and (b) active and reactive power transients (P_1, P_2, Q_1, Q_2).

5.6 Static Capacitor Exciter Stand-Alone IG for Pumping Systems

Considering the energy storage capacity/water pumping in a reservoir for later use seems to be one of the best ways to use wind energy, which has a supply that is time dependent (by day and season). As variable speed is useful, to tap most of the wind energy from cut-in to cut-off wind speeds, the frequency of the voltage generated by the IG varies markedly, but the ratio V/f does not vary much. For induction-motor-driven pumps, such a situation is adequate. Consequently, the frequency of the IG does not need to be controlled at induction motor terminals. To provide controlled voltage at various speeds, the single value capacitor needed to self-excite the IGs must be varied. A static capacitor exciter (SCE; [Figure 5.20](#)) does just that.

The static exciter handles only the reactive power requirements of both the IG and IM through adequate control [15,16].

For self-excitation, the magnetic flux in the IG has to remain above a certain level, and the output voltage V_G proportional to IG speed ω_G must be producing a good approximation to that. If speed feedback is not available, a V_G proportional to frequency ω_1 will do the job.

A vector control system that keeps both the capacitor voltage and the generator voltage proportional to speed (or frequency) is shown in [Figure 5.21](#).

The stator flux in the IG is close-loop controlled (rather than imposed only) through the generator voltage amplitude regulator along the i_d channel.

The DC capacitor voltage is also PI controlled to correspond to generator voltage proportional to speed.

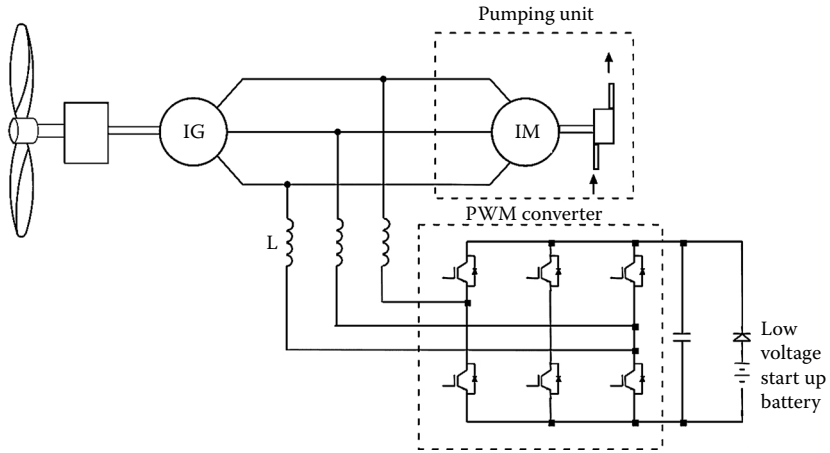


FIGURE 5.20 Static capacitor exciter (SCE) stand-alone induction generator (IG) for water pumping.

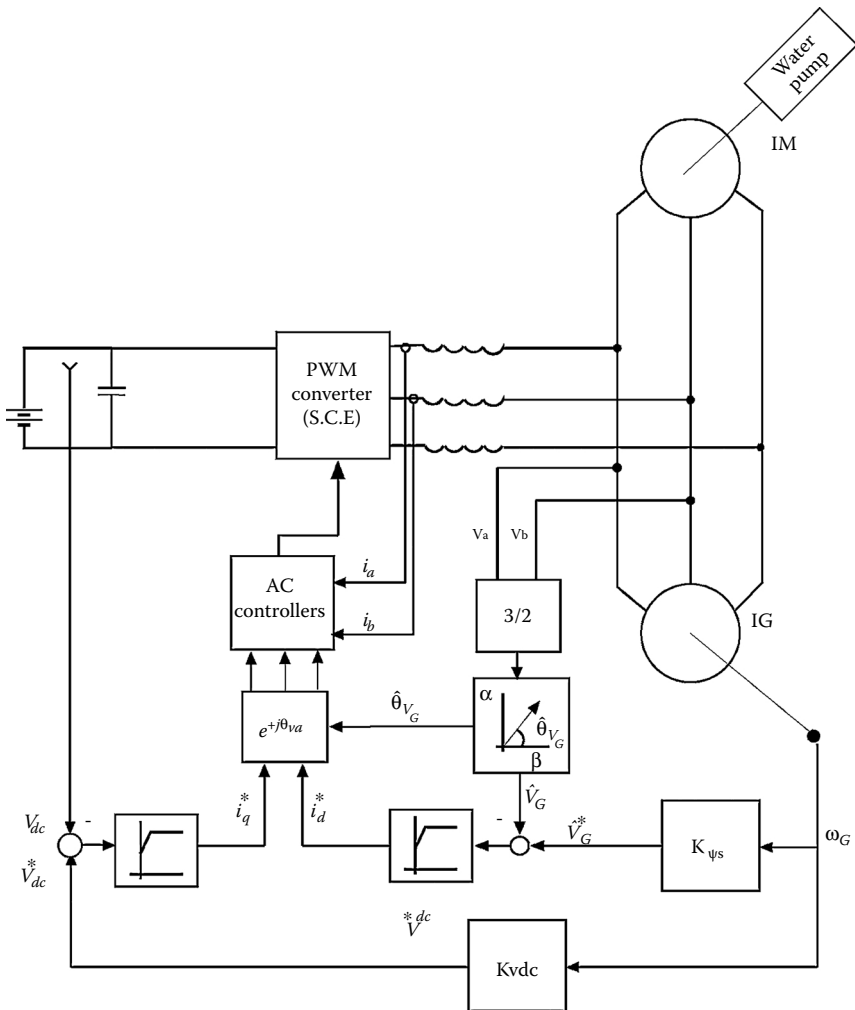


FIGURE 5.21 Vector control of static capacitor exciter (SCE) induction generator (IG) for induction machine (IM) water pumping system.

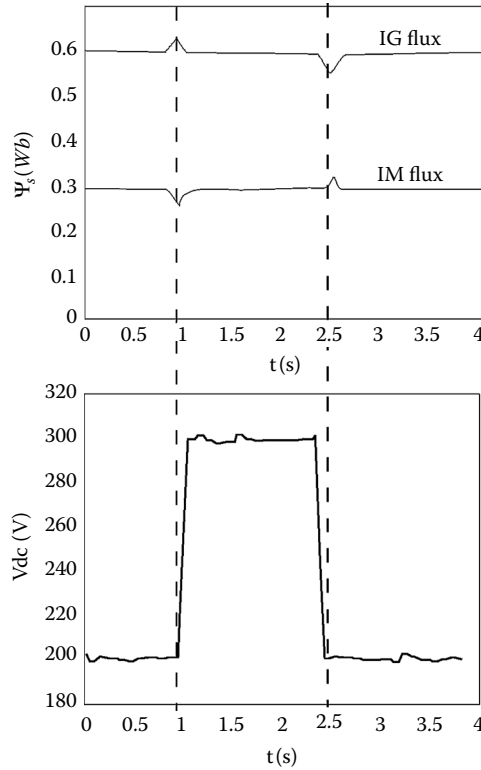


FIGURE 5.22 Stator flux Ψ_s and capacitor voltage V_{dc} transients during speed ramping from 1200 rpm to 1800 rpm and then back to 1200 rpm.

As the magnetization current in the machine is maintained rather constant through V/f control, the equivalent value of the capacitor is inversely proportional to speed. The IG stator flux is, thus, constant over a wide range of speeds. The induction motor flux should also be constant with generator speed (V/f control).

Typical behavior of such a system [16] is depicted in Figure 5.22, where the speed is ramped from 1200 to 1800 rpm and back. The IG and IM flux and capacitor voltage V_{dc} are recorded.

As expected, the response is smooth and stable. The centrifugal characteristics are such that the pumping flow rate Q varies proportionally with wind speed, until the maximum power ceiling of the stall regulated wind turbine is reached.

5.7 Operation of SCIGs with DC Voltage Controlled Output

Variable speed operation with some stator converter control of cage rotor IGs may be obtained at reasonable costs if DC voltage controlled output is considered. DC loads with battery backup are a typical application for stand-alone operation.

When the SCIG is part of a group of generators to be paralleled, on a common DC voltage bus, with a single inverter to connect the group to a local power grid or to a cluster of AC loads, the same situation occurs.

Offshore wind farms are a typical example, as is a group of microhydrogenerators. In principle, the SCIG is self-excited through a static exciter (SCE; Figure 5.20 and Figure 5.21). The IG is designed to produce a voltage that even at maximum speed will need a bit of boosting through the diode rectification and filtration, in order to produce fast controlled constant DC voltage output (Figure 5.23).

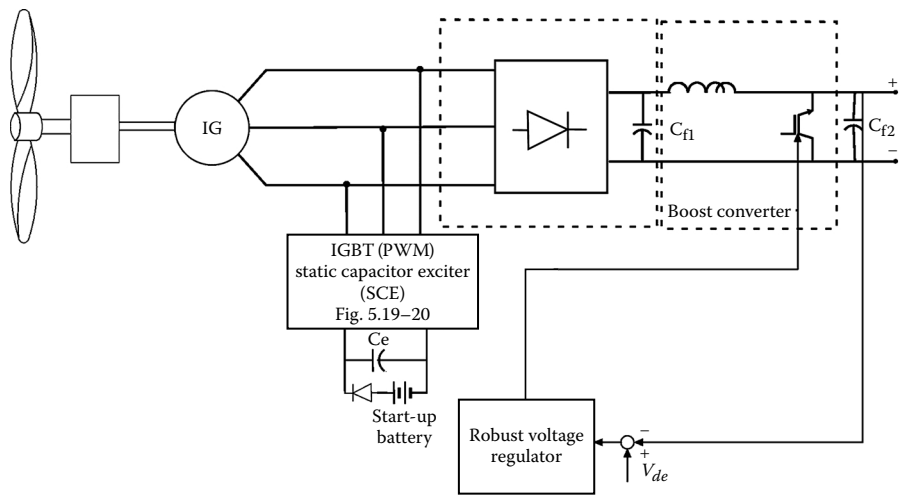


FIGURE 5.23 Static capacitor excited (SCE) induction generator (IG) with controlled direct current (DC) voltage output.

If the IG is built with a rather high rated power factor (above 0.8), the SCE is designed for partial power (reactive power) ratings (below 0.6 per unit [P.U.]) and, thus, for lower costs.

In essence, as described in a previous paragraph (Figure 5.21), the generator voltage increases proportionally to speed. Consequently, the capacitor rating is minimum. The diode rectifier with capacitance filter provides for the active power input to the boost DC–DC converter with filter. A DC voltage robust regulator regulates the output DC voltage.

The boost converter makes use of an IGBT power switch for sufficient switching frequency to reduce the size of the output filter (f_1) C_{f2} . The boost converter may also be implemented with three AC power switches (with six thyristors of partial rating) connected to the diode rectifier median point (Figure 5.24) [17].

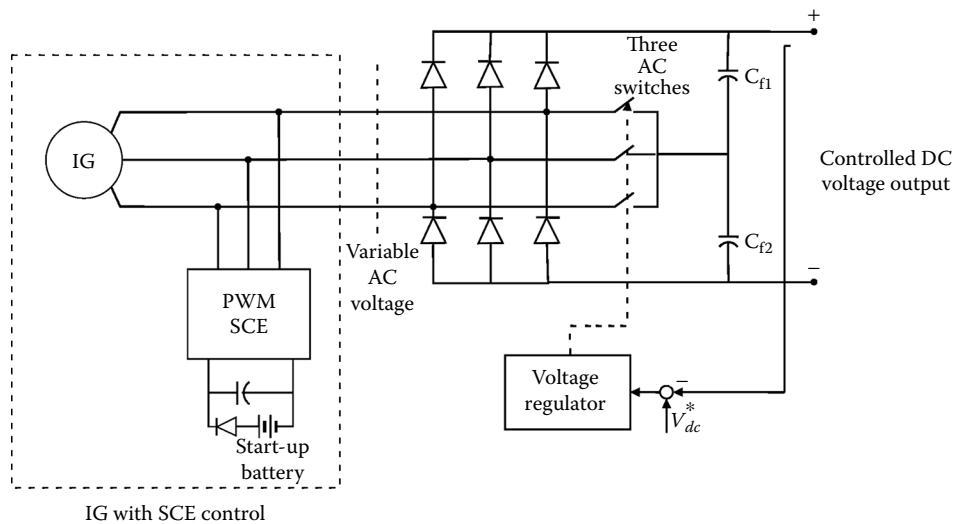


FIGURE 5.24 Static capacitor excited (SCE) induction generator (IG) with median point diode rectifier voltage booster and direct current (DC) controlled output.

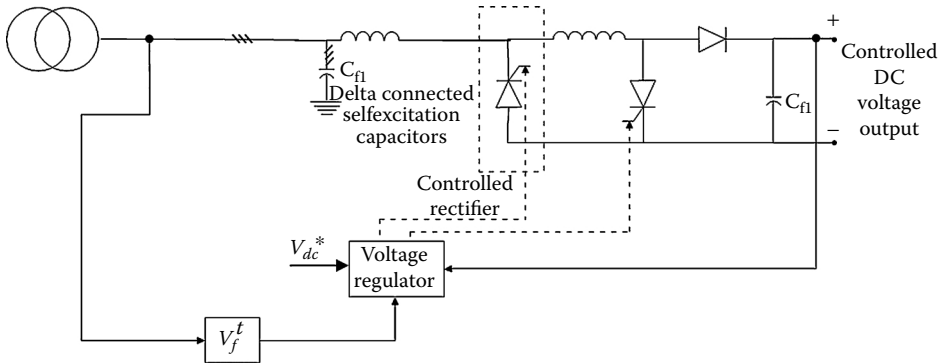


FIGURE 5.25 Self excited induction generator (SEIG) with controlled rectifier and voltage booster.

The voltage boost is provided by the capacitance C_{f1}, C_{p2} as energy storage elements. The three AC (bidirectional) thyristor switches of partial ratings plus the capacitance C_{f1}, C_{p2} are expected to cost less than the single IGBT and the inductor energy storage element.

The diode rectifier generally provides on the input side a unity power factor for the fundamental. Consequently, no reactive power is transferred on the DC side for the scheme in Figure 5.23. The phase delay action of the thyristor switches in the median point voltage booster slightly modifies this situation, but the capacitor energy storage elements C_{f1} and C_{p2} compensate for it. The capacitance required for the same DC voltage output ripple should be larger for the latter case, as the thyristor switching frequency is less.

It is also possible to use the uncontrolled capacitor self-excited IG, a fully controlled rectifier to reduce the DC output voltage at higher speed, and an inductor plus a IGBT switch voltage booster with a capacitance filter (Figure 5.25).

The thyristor rectifier lowers the generator voltage, which tends to increase with speed, while the booster increases it to maintain the output voltage constant with speed. The concerted action of rectifier and booster control is to produce fast and stable DC voltage control. At light load, the rectifier absorbs almost only reactive power to produce controlled IG terminal voltage. Operation of the controlled rectifier at large delay angle (almost 90%) is not appropriate for DC load voltage control.

The operation is proper when the boosting stage is at work. So, the minimum reference voltage V_{dc}^* (Figure 5.25) has to be higher than the maximum voltage of the rectifier for 1.0 P.U. IG voltage [18].

As expected, in all of the above schemes, load rejection, for constant speed, does not produce significant overvoltage transients. In the SCE schemes, the failure of the SCE or voltage booster control at maximum speed does not produce severe overvoltages to the diode rectifier, as the IG de-excites quickly in the process. This is not so for the controlled rectifier scheme, where the whole capacitor remains connected at the generator terminals.

Connecting a few such SCE IGs in parallel on the DC voltage bus poses not only the problem of voltage stabilization at a constant value, but also the problem of power sharing. Changing slightly the reference voltages V_{dc}^* of various SCE IGs, based on voltage to power droop curves, is appropriate for the scope of our discussion here (Figure 5.26 for two SCE IGs).

The total load power is divided between the SCE IGs in parallel, based on the energy availability and minimum risk or other criterion, accordingly, to voltage vs. power droop curves calibrated at commissioning.

The power of each SCE IG system, on the DC side, has to be measured, and, eventually, close-loop voltage droop setting is performed.

Note that a secondary stator winding may be used and supplied through an SCE to improve the characteristics of a self-excited (with fixed capacitors) primary AC output IG [18].

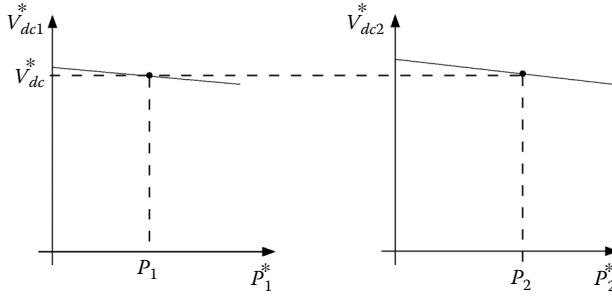


FIGURE 5.26 Direct current (DC) voltage vs. power droop curves.

Though some reduction in frequency variation was obtained, the flexibility of the solution is still limited in terms of speed for frequency-sensitive loads. The solution is similar in effect to the SCE IG, but it costs more, as the IG is provided with dual windings.

5.8 Dual Stator Winding for Grid Applications

A dual stator winding cage rotor IG [19,20] may have a main three-phase winding with p_1 pole pairs, designed at 100% rated power, and an auxiliary three-phase winding with p_1' pole pairs ($p_1/p_1' = 2/3, 3/4$) designed at around 25% power rating. Alternatively, two separate such machines may be placed on the same shaft (Figure 5.27a and Figure 5.27b).

The 25% rating cascaded (bidirectional power convertor has four-quadrant control capabilities for 25% of rated power of the main winding [generator]) and may be at work when the following conditions are met:

- Load is below 25%, and the main winding (IG) is turned off
- The main winding (IG) is at work above 100% power, and additional power is available at the prime-mover shaft and should be delivered to the power grid

The larger number of poles ($p_1 > p'$) makes the auxiliary winding (IG), fed at variable speed, suitable for lower speeds. Also, with $p_1'/p_1 = 2/3, 3/4$ not very different from unity, less than 150% of power grid frequency is needed in the auxiliary winding fed through the AC–AC converter to add power at speeds between synchronous and peak torque speed for main winding.

As motoring and generating are feasible, through the PWM AC–AC converter, the latter may also be used to damp the rotor oscillations due to natural variations (wind gusts, tower shadow blade pulsations, etc.) in wind speed.

As the number of poles of the two windings $2p_1$ and $2p_1'$ are different than each other, there is no main flux coupling between them other than through the leakage flux, which may be neglected, to a first approximation.

The two windings are fed with voltages of two different frequencies ω_1 and ω_1' , and their rotor currents may have different frequencies: $\omega_2 \neq \omega_2'$. So, the two windings interact with the rotor cage independently, and thus, they may be modeled separately, as in the case of two IGs (Figure 5.26) that have the pertinent rotor parameters.

Typical steady-state characteristics, shown in Figure 5.27, may look like those of the pole-changing SEIG in Chapter 4, but the auxiliary winding IG is now capable of four-quadrant smooth operation in a roughly –50% speed range, with notable reactive power exchange capability. The 25% rating was taken

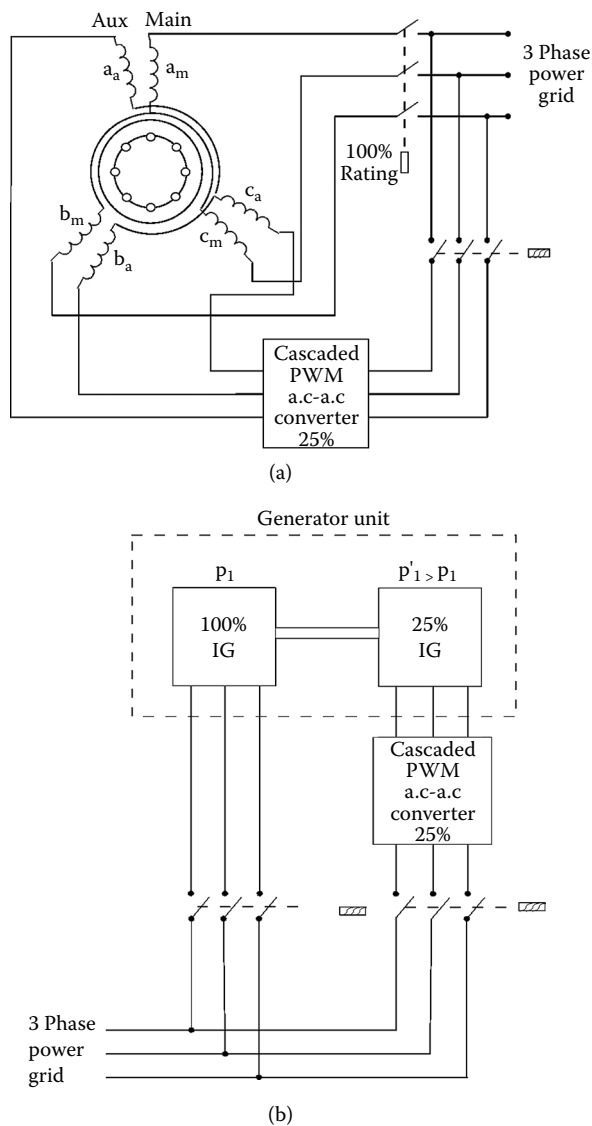


FIGURE 5.27 Dual stator converter controlled induction generator (SCIG) for power grid applications: (a) with dual stator winding and (b) with dual induction generator (IG).

as a good compromise between additional costs and performance gains (Figure 5.27). The transients in the power grid may be reduced through the PWM AC–AC converter control.

Note that the dual stator winding concept was proposed for widely different pole counts in variable speed IM drives with two PWM converter controls in order to provide for more controllable torque at very low speeds [20].

Static converter full power control may also be used for single-phase AC power grids in remote populated areas. As only the load-side PWM converter is changed to a single phase one, this case will not be treated further here (see Reference [18] for more details).

Cage IG design is similar to motor design for variable speed with special attention paid to losses and overspeeding. For details, see Reference [1], Chapters 14 through 18.

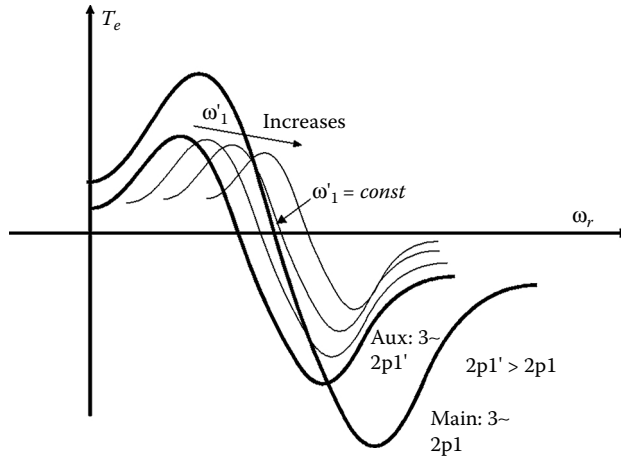


FIGURE 5.28 Torque vs. speed curves of an induction generator (IG) with auxiliary stator winding four-quadrant power converter control.

5.9 Summary

- Cage rotor IGs connected directly to the power grid ([Chapter 4](#)) behave rigidly, causing severe transients both in the power grid and in the IG torque. To soften this behavior and tap most of the prime-mover energy (wind turbines, for example), or reduce fuel consumption (in diesel engines), variable speed generation at constant voltage and frequency power grid is required.
- Full power bidirectional (four-quadrant AC–AC) PWM static converters are that soft interface between IG and the power grid at variable speed. They are called here SCIGs.
- Four-quadrant PWM static converters may be of cascaded (indirect) type or of direct (matrix) type.
- Only the back-to-back voltage source PWM converters are available off the shelf up to 1 megawatt (MW) per unit and more for special orders.
- In the cascaded PWM AC–AC converter, direct torque and flux control strategy may be applied to the machine-side converter, and vector control is adequate for the machine-side converter. The prime-mover optimal use leads, finally, to an almost linear power vs. speed curve, with a limiter. The machine-side converter may be torque controlled with torque reference calculated from power reference vs. speed of wind or hydroturbine or diesel engine.
- DTFC of machine-side converters seems the natural choice. The reference stator flux may be calculated as torque and speed dependent, to reduce IG losses at all speeds.
- An implementation case study with sliding mode flux observers and torque and flux controllers for sensorless control is illustrated in the chapter. Space-vector modulation in the machine-side PWM converter is added to reduce current, flux, and torque ripple. The same implementation would work for machine-side PWM converters.
- The grid-side converter is vector controlled with orthogonal axes aligned to grid voltage vector.
- Along axis d (voltage vector position), active power exchange is provided through DC link voltage and d axis current controls that output V_d^* . Along axis q , the grid voltage is regulated, and its regulator output commands the reactive power reference.
- Cascade reactive power and i_q regulators then provide V_q^* .
- After transformation to $V_a^* V_b^* V_c^*$, the three AC voltages are produced by the inverter through PWM techniques.
- The cascaded AC–AC PWM converter provides for smooth motor starting and then motoring or generating to the power grid. The standard synchronization sequence is fully eliminated. Safe and soft connection and disconnection to the power system are inherently available.

- Up to $\pm 100\%$ reactive power exchange with the power grid is available, which eliminates the external capacitor bank, with its stepwise control so typical and problematic in fixed speed IGs at the power grid.
- Experimental work on a 10 kW unit is solid proof of these claims. The price to pay for this performance is the additional costs of the four-quadrant PWM AC–AC converter.
- Stand-alone operation of SCIGs occurs when during operation at power grid, full load rejection is required or when the system is designed for separate loads.
- In stand-alone operation, the machine-side converter control stays the same as for power grid operation. The load-side converter control changes markedly, from current control type to voltage control type.
- For stand-alone operation, the DC link voltage control imposes on the V_d (load voltage in synchronous coordinates) control, with given frequency. Voltage decoupling of the filter (ωL_i) might also be added. Good voltage response to sudden load increase was demonstrated.
- Parallel operation of stand-alone SCIGs leads to paralleling of voltage source inverters.
- To provide for desired power sharing between SCIGs of the group ΔV_1 vs. P_i , Q_i droops are used as for synchronous generators in power systems [21].
- Static capacitor exciters (SCEs) at IG terminals are a lower cost alternative to control the IG terminal voltage. For variable speed operation, the terminal voltage is kept proportional to speed, as the DC (capacitance) voltage does. For induction motors, this is equivalent to V/f , variable frequency scalar control, ideal for centrifugal water pumps.
- The same SCE solution, but with rectifiers and DC voltage booster, may provide constant DC output voltage output at variable IG speed. Again, the SCE is vector controlled. IG voltage speed and capacitance voltage are kept proportional to speed (frequency) to maintain large stator flux in the IG, which is needed for self-excitation.
- Load rejection in SCE IG, when all power electronics elements are faulting, does not lead to dangerous overvoltages, as the IG de-excites rapidly.
- Dual stator winding IGs or dual IGs, one of 100% power rating and the other of about 25% power rating and slightly larger pole count $2p_1'/2p_1 > 1$, were also investigated.
- The lower power rating winding (machine) is connected to the power grid through a four-quadrant AC–AC PWM converter. The main winding (or IG) is connected directly to the power grid.
- The four-quadrant AC–AC PWM converter may work alone below 25% rated power at lower speed, or it may assist the full power winding (IG) with up to 25% more power, or it may help in damping the prime-mover torque oscillations.
- IG design for variable speed is similar to IM design for variable speed. For more details, see Reference [1], Chapters 14 through 18.

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